KUELCKE

Calibration of Pitot Tubes

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CALIBRATION
OF
PITOT TUBES

...BY...

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This is to certify that the following thesis prepared under the direction of Professor A. N. Talbot, Head of the Department of Municipal and Sanitary Engineering, by

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entitled CALIBRATION OF PITOT TUBES

is accepted by me as fulfilling this part of the requirements for the Degree of Bachelor of Science in Civil Engineering

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THE CALIBRATION OF THE PITOT TUBE AND THE COLE-FLAD PITOMETER.

In this thesis the work of calibrating or determining the coefficient for Pitot tube No.10 belonging to the Mississippi River Commission and of a Cole-Flad pitometer will be described and recorded and a discussion of the results made.

The writer will first take up the development and use of the Pitot tube and give his experimental work with it and will follow this with the calibration of the Cole-Flad pitometer.

CALIBRATION OF THE PITOT TUBE.

The Pitot tube was invented by the French hydraulic engineer Pitot in 1750. In its simplest form it consists of a bent tube, the mouth or point being so placed as to directly face the current for which the velocity is to be determined. The water rises to a height h in the vertical part of the tube above the surface of the flowing stream, giving a measure of the velocity according to the formula $v=\sqrt{2gh}$. Latera second tube was added making two tubes placed side by side with their submerged mouths at right angles so that when one opening faces the current the other is perpendicular to it.

This instrument was improved later by Darcy and Bazin. They improved it by using two tubes, one tapering to a fine point and facing up stream, while the other was provided with small holes on the top and bottom. The tops of the two tubes were connected, so that a partial vacuum formed above the liquid causing it to rise to a height convenient for reading. These experiments were

published in 1865. For the tube just described Darcy and Bazin found that by using the formula $v = c\sqrt{2gh}$, the coefficient c was approximately equal to unity.

The Pitot tube has the advantage that no time observation is needed to determine the velocity, but its disadvantage is that the height h is usually small, so that an error in reading has a large influence. Nothing was done with this instrument for a long time after these experiments were made, as it was regarded as an instrument with a low degree of precision.

The first measurement of velocities of filaments were made by Freeman in 1888 with the Pitot tube. The experiments were made on jets from fire nozzles and also from 1 1/8-in. tubes under high velocities. The velocities were practically constant for smooth nozzles for a distance 0.6 of the radius from the center, and then rapidly decreased. For pipes the velocities decreased quickly near the center, but more rapidly toward the surface.

In 1893 Bazin made experiments with the Pitot tube on jets from standard orifices. Experiments on flow in pipes with Pitot tubes were made by Cole in 1897, and by Williams, Hubbell, and Fenkell in 1899. (Trans.Amer.Soc.C.E. 1902 vol.47). The results obtained by these men with the Pitot tube established the fact that this instrument is one of great precision for the measurement of velocities in pipes.

In the experiments made by these men much irregularity is obsrved in the velocity curves plotted from actual measurements, this being due to pulsations in the water, and to errors of observations.

The experiments with the Pitot tube which are to be described in this thesis are similar to those made by Mr.J.F.Peterson, U. of I."04, (Calibration of the Pitot tube, Thesis, University Library). Mr.Peterson's experiments were suggested by Assistant Engineer F.B.Maltby of the Mississippi River Commission. In 1902, Mr.Maltby made a series of efficiency tests on the hydraulic dredges used by the Mississippi Commission. Pitot tubes were used to determine the velocities of flow in the discharge pipes and suction pipes of the dredges. The pipes used ranged in size from 16 to 34 inches with a velocity of flow from 6 to 25 feet per second. The several tubes there used were found by calibration with floats to have a coefficient of unity. The tube used in these experiments is similar to No.9, the only difference being that the bent portion of the tube is shorter.

The experiments were made with the 12-in., 8-in., and 6-in. pipe in the Hydraulic Laboratory of the University of Illinois. All of these pipes are connected to the 60-foot stand pipe in the laboratory, and also to the two pumps located directly over a sump in the laboratory. The pump used for supplying low velocities is a Stilwell-Bruee duplex direct acting, and pumps either directly into the pipes or through the stand pipe into the pipes under a constant head of 20 feet. A centrifugal pump was used for high velocities discharging the water into the pipes as did the one previously described. Both pumps may be used at one time for giving a larger flow and discharge either directly into the pipes or through the stand pipe. To ensure a constant flow an overflow pipe was attached to the stand pipe, so that a constant head of about 20 feet could be obtained, provided

sufficient water was pumped to maintain this head. Pumps and valves could be adjusted so that a small amount of water was always discharged through the overflow pipe. This reduced the pulsation of the water and gave a steady flow through the pipes. The pipes discharge into the sump through a long channel. Two weirs have been built in this channel, the upper one being a 3-ft. weir with end contractions, and the lower one a 3-ft. weir with suppressed end contractions. These were both calibrated by Mr.A.C.Le Sourd, U. of I. "03 (Calibration of Weirs in the Hydraulic Laboratory of the University of Illinois, Thesis "03). The lower weir was used and his coefficients adopted in measuring the discharge.

The Pitot tube used consists essentially of two pipes, the outer one being a 3/4-in. pipe and the inner tube 1/8-in. The latter is called the velocity or impact tube, and the former the static tube. The 1/8-in. tube runs along the inside of the 3/4-in. pipe, and terminates in a $\frac{1}{4}$-in. cock. The outer pipe has four holes of 1/16-in. diameter, to determine the static pressure. The interior tube is connected through the upright pipe, and the handle to another $\frac{1}{4}$-in. cock. These cocks are each connected by rubber tubing to a differential gauge. A sketch of this apparatus is shown in Mr.Peterson's thesis "04. Two holes were tapped in each laboratory pipe used and a stuffing box was screwed in, one being at the side and one at the bottom. The stuffing box is so arranged that the tube can be moved through it on a line with the horizontal and vertical diameter of the pipe.

For the purpose of observing with the Pitot tube, a differential gauge was used. This consisted of two parallel $\frac{1}{4}$-in.

glass tubes connected at the top to the Pitot tube with rubber tubing, and having a scale divided into inches and tenths of inches between the glass tubes. These glass tubes were about seventy inches long enabling a high velocity to be measured, when a liquid of medium density is used. This tube was filled about half full with carbon tetrachloride, a colorless liquid whose specific gravity is about 1.60. Readings of this liquid were taken occasionally to obtain the amount and constancy of its specific gravity. Since the specific gravity of the liquid is different from that of water, it was necessary to determine the head of water which corresponds to the actual head as read on the scale. Let h' equal the head as read from the gauge, h the corresponding water head, and x the specific gravity of the liquid. The relation is $h = h'x - h' = h'(x-1)$

Since the velocity of water in the pipe varies throughout the cross section, it was necessary to traverse the diameter of the pipe with the instrument i.e., to make observations with the point of the tube at various points along the diameter and note the gauge readings. With these heads and their square roots obtained, a curve was plotted giving the relative velocities at different points along the diameter. In order to simplify the reductions and give the positions equal weight, the area of the pipe was divided by a series of concentric circles into a central core and concentric rings of equal area, and the velocities found at the center point of each of these annular areas. The mean of these velocities was then computed and this mean was taken as the mean velocity of the water. It was found an important area was left untraversed with this tube near the surface of the pipe.

[illegible]

[illegible]

The point of the tube could not be brought closer than ½-in. to the wall of the pipe. In order to determine the character of this velocity curve a Cole-Flad pitometer was used which was brought within 1/8 inches of the wall. The square roots of all these readings were taken and when plotted it was found that the curve of distribution of velocities approximately represented an ellipse.

One of the most difficult things encountered was to eliminate from the instrument the air which had accummulated in the pipe while it was filling with water. The best method to overcome this difficulty is to connect the rubber tubing to the Pitot tube but leave the differential gauge disconnected until all the air is out of the pipe. Next turn on the water and discharged it for a few minutes through the pipe, at the same time let the water run through the Pitot tube and the rubber tubing. Then shut the discharge valve of the pipe but allow the water still to run through the tubing. While the water is flowing connect the differential gauge, holding the finger over one glass tube while connecting one rubber tube. As soon as one tube has been connected and the pinch cock closed, connect the other side. The liquid can now be brought to the same level in the gauge by manipulation of the pinch cooks.

To simplify computations a constant was deduced which if multiplied by the square root of reading in inches will give the velocity in feet per second as registered by the gauge for a coefficient of unity. We have $v = \sqrt{2gh} = \sqrt{64.32h}$

By changing h to the equivalent water head and also $h = h'(x-1) = 0.6h$,

we get:-

$v=\sqrt{64.32\times\frac{0.6h}{12}}=1.79\sqrt{h}$ (where h is in inches). As the pipes are tapped in two places in each pipe, one at the side and the other at the bottom, it was thought advisable to make two traverses, one at the bottom and one from the side with the same head on the weir. In this way if there was an uneven distribution of velocity throughout the cross section, the mean value for the two curves would tend to give more uniform and accurate results.

Plates I to IV show the elliptical character of the velocity curve for the 6-in., 8-in., and 12-in. pipes as obtained by using the Pitot tube. The values of the $\sqrt{h}$ in inches were plotted as abscissas and the ordinates represent the diameter of the pipe. To get the velocities indicated by the Pitot tube (coefficient unity) multiply the value of $\sqrt{h}$ by 1.79. Plates I and II represent the curves for the 6-in. pipe. The coefficient for the instrument (ratio of the actual velocity to the indicated with Pitot tube) varied from .941 to .981, giving an average coefficient of .956. Table 1 has the ratios of the mean velocity to the center velocity. These values vary from .846 to .912 and give average value of .880.

Plate II shows the results obtained with the 8-in. pipe. The coefficient varied from .950 to .985, giving an average coefficient of .963. The values obtained for the ratio of the mean velocity to the center velocity varied from .843 to .907, giving an average of .869. Plate III gives the results of the 12-in. pipe. The coefficient varied from .945 to .985 giving an average value of .966. For the ratio of the mean velocity to the center velocity the values varied from .859 to .894 giving

an average value of .873.

As seen from the results obtained with the Pitot tube the coefficient c varies from .940 to .985 and has an average value of .960. The extreme variation may be due to (1) the tube itself giving variable results, (2) errors in making traverses, (3) opportunity for errors in the method used. The first may be considered a probable error, ~~and~~ as tubes of similar construction have been rated giving results which had a range of several per cent. To avoid the error of (2) each traverse was carefully checked by repeating the observation at some of the points. To avoid the error of (3) traverses were were run along both horizontal and vertical diameter with the same head on the weir and mean values taken for each point along the diameter. The latter seems to be very important, as it tends to give a uniform curve.

The experiments made by Mr.Maltby were made with large pipes varying in size from 24-in. to 34-in. For the coefficient c he used a value of unity. For the ratios of the mean velocities to the center velocities his values varied from 0.800 to 0.971 giving a mean value of 0.872 for all the dredge pipes used. These variations for individual determinations seldom varied more than 2 to 3 per cent for any one dredge.

The Pitot tube was rated by Mr.Maltby in open running water having a velocity of about 3½ feet per second by comparing it with floats. The writer is of the opinion that in the calibration in open running water a range of velocities should be used, as the conditions may change in using higher or lower velocities. It is also difficult to get the exact velocity for the point of the

channel where the instrument is placed. The floats may have a tendency to deviate some what from the center of the channel, and if this is true the velocity for the float and the instrument would be different.

CALIBRATION OF THE COLE-FLAD PITOMETER.

Another instrument used to determine velocities in pipes is the Cole-Flad pitometer. This device was invented in 1896 by Mr.Edward S.Cole of Chicago, Illinois, and Mr.Henry Flad of St.Louis, Missouri. This pitometer was used in determining the amount of water flowing through the water mains of Terre Haute, Indiana, and proved to be very efficient, as well as cheap and accurate. Water surveys were also carried on with this instrument at Columbus, Ohio; New York City; The Burrough of Manhattan; and Brooklyn. In all of these surveys this instrument proved very efficient.

The Cole-Flad pitometer consists of two pitot tubes so arranged that each may slide seperately through the cap of a corporation cock. This corporation cock is the same size as that used in the previous experiment, and is connected in the same way to the pipe. From the side of the corporation cock a short tube leads to the air. This may be connected to a pressure gauge so that the water pressure can be read at the same time the deflections are being recorded. The Pitot tubes have an internal diameter of 1/8 inches and are connected to ¼-in. rubber tubes. The curve portion of the pitot tube is provided with cut water edges, so that the velocity will not be reduced by contact with the tube. The connections of the Cole-Flad pitometer with the differential gauge will not be discussed here, as they were the same in every particular as those used in the experiment with the Pitot tube. The scale and the plotting of the velocity curves were also the same as was used in the previous experiment. The

area of the pipe was also divided by a series of concentric circles into a central core and concentric rings of equal area and the velocities found at the center point of each of these annular areas, so as to give the positions equal weight. The liquid used was carbon-tetrachloride having a specific gravity of 1.60. The formula $v = \sqrt{2gh} = \sqrt{64.32h(x-1)} = 1.79h$ was made use of the same as with the Pitot tube.

In the calibration tests made by Mr.Cole various schemes were used. In some of the tests made at Terre Haute, Indiana he used a series of cast iron water pipes placed end to end, obtaining water from a reservoir giving a constant pressure of 10 lbs. per sq.in. The pipes varied in size from 6-in. at the upper and lower ends to 12-in. in the middle. Pitometers were used for each size of pipe and the water was measured by means of a calibrated weir. At the Twenty-Second Street pumping station in Chicago, Mr.Cole made some calibration tests on a 4-in. semi-circular trough made of galvanized iron. Floats and a stop watch were used to determine the actual velocities. Calibration tests similar to Mr.Cole were made at the University of Illinois by Mr.G.L.Sawyer (Calibration of Cole-Flad Pitometer, Thesis, U. of I. "03). In place of using a galvanized iron trough, Mr.Sawyer used an 8-in. wrought iron pipe cut longitudinally through the center and the ends so joined together as to make a 40-ft. semi-circular channel. A coefficient of .80 was obtained in these experiments.

After considering the various methods used and others that might be used, it was decided to adopt the scheme used in the experiment with the Pitot tube i.e., obtain the velocities

in the 12-in., 8-in., and 6-in. pipes with the Cole-Flad pitometer. The writer will not go into any details as to the connections of the instrument with the differential gauge, connection of the instrument with the pipes, or the source from which the water was obtained, as the experiments were carried on in the same manner as in the previous experiments with the exception that the Cole-Flad pitometer was used instead of the Pitot tube No.10.

Plate V to VII show the elliptical character of the velocity curve of the 6-in., 8-in., and 12-in. pipes as obtained by using the Cole-Flad pitometer. The values of the $\sqrt{h}$ in. inches were plotted as abscissas and the ordinates represent the diameter of the pipe. The indicated velocities at any point may be found by multiplying the value of $\sqrt{h}$ by 1.79. Plate V represents the curve for the 6-in. pipe. The coefficient c varies from .800 to .835 giving an average value of .815. Plate VI gives results obtained with the 8-in. pipe. For this pipe the coefficient c varied from .805 to .832 giving an average value of .812. Plate VII gives the results with the 12-in. pipe. The coefficient c varies from .796 to .812 giving an average value of .806. From Table II the values obtained for the ratio of the mean velocity to the center velocity for the 6-in. pipe varied from .848 to .881, giving an average value of .863. For the 8-in. the values varied from .840 to .895 giving an average value of .873. For the 12-in. the value varied from .914 to .969, giving an average value of .937. The coefficient c obtained by Mr.G.L.Sawyer with the semi-circular pipe varied from .79 to .82 giving an average .80.

The results of the calibration tests seem to show that both the Cole-Flad pitometer and the Pitot tube are accurate instruments if properly and carefully manipulated. Both of these instruments are doubtless as economical as there are at present on the market. They are not expensive to construct, or to install and the cost of operation is low.

PLATE I

Curves showing values of $\sqrt{h}$ using

Pitot Tube

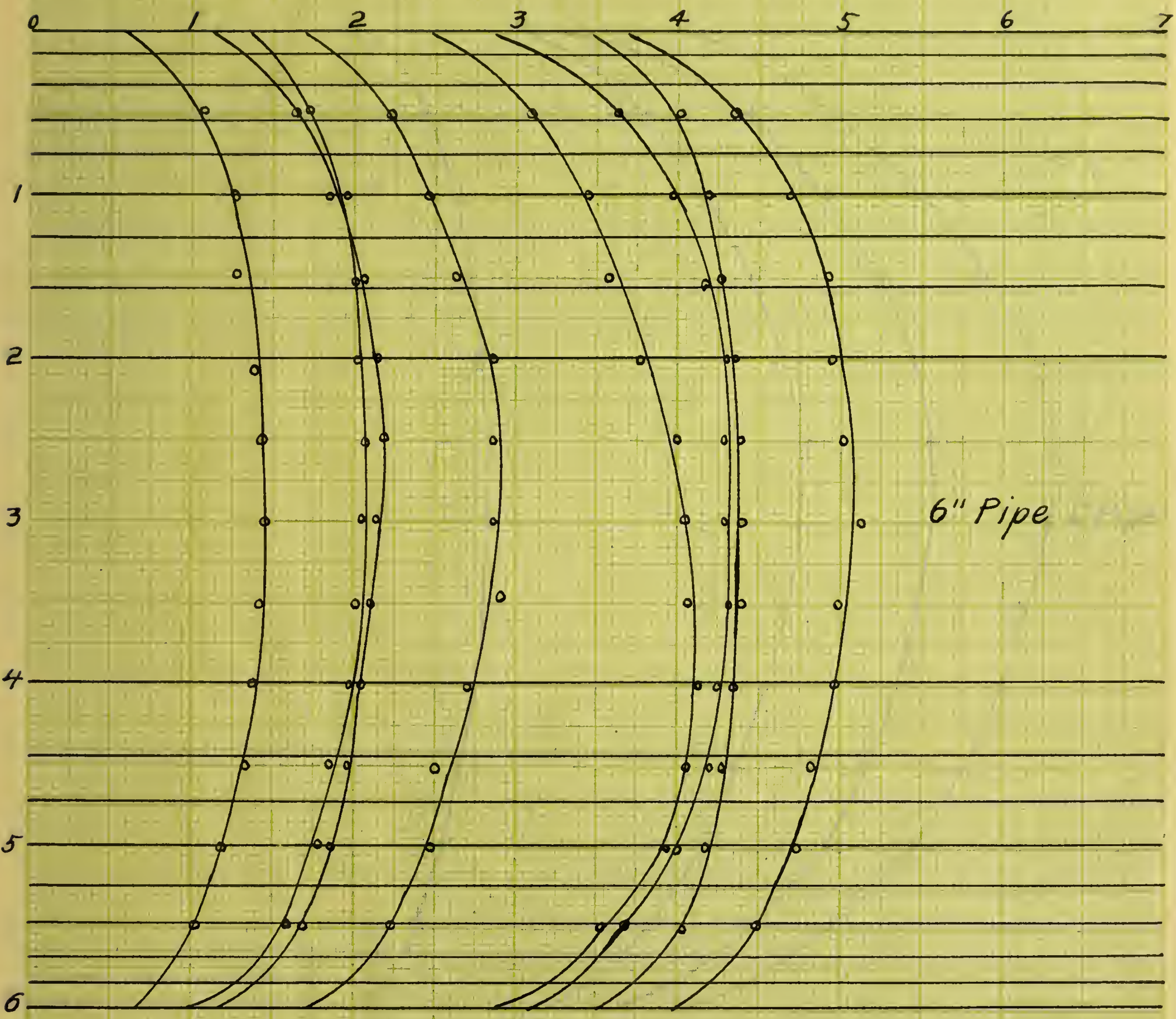


PLATE II

Curves showing values of $\sqrt{h}$ using

Pitot Tube

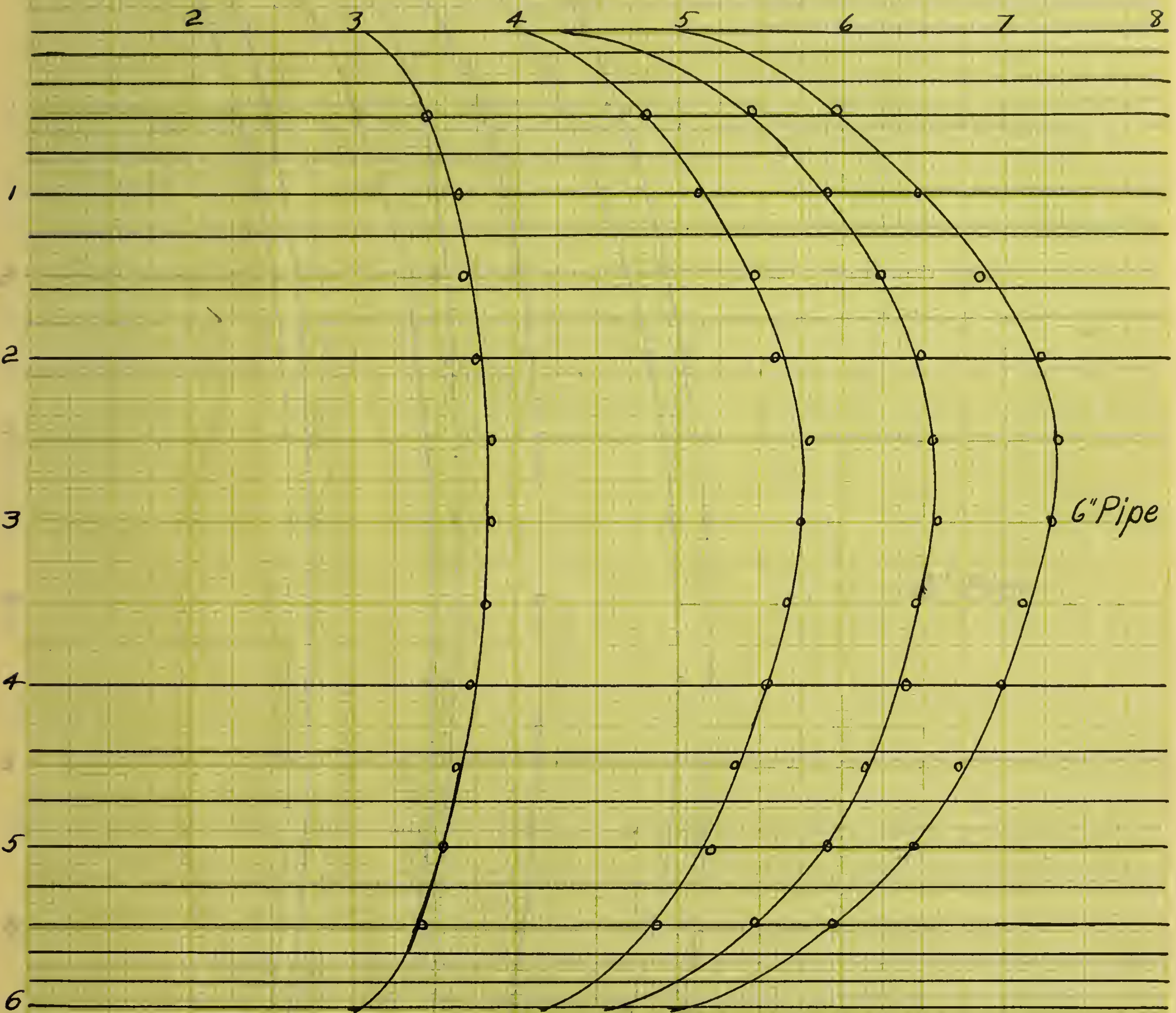


PLATE III

Curves showing values of $\sqrt{h}$ using

Pitot Tube

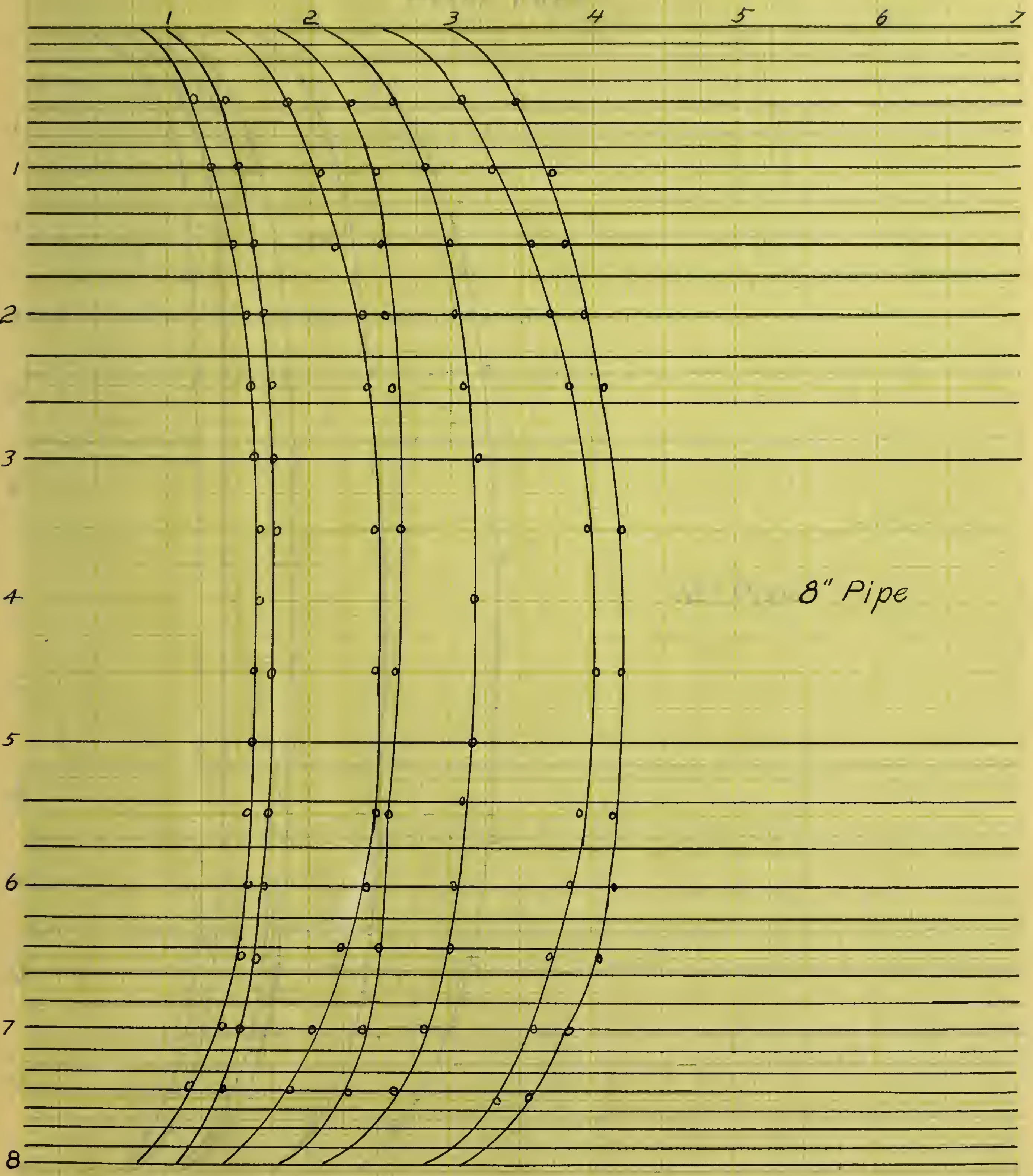


PLATE III

Curves showing values of N using

Pitot Tube

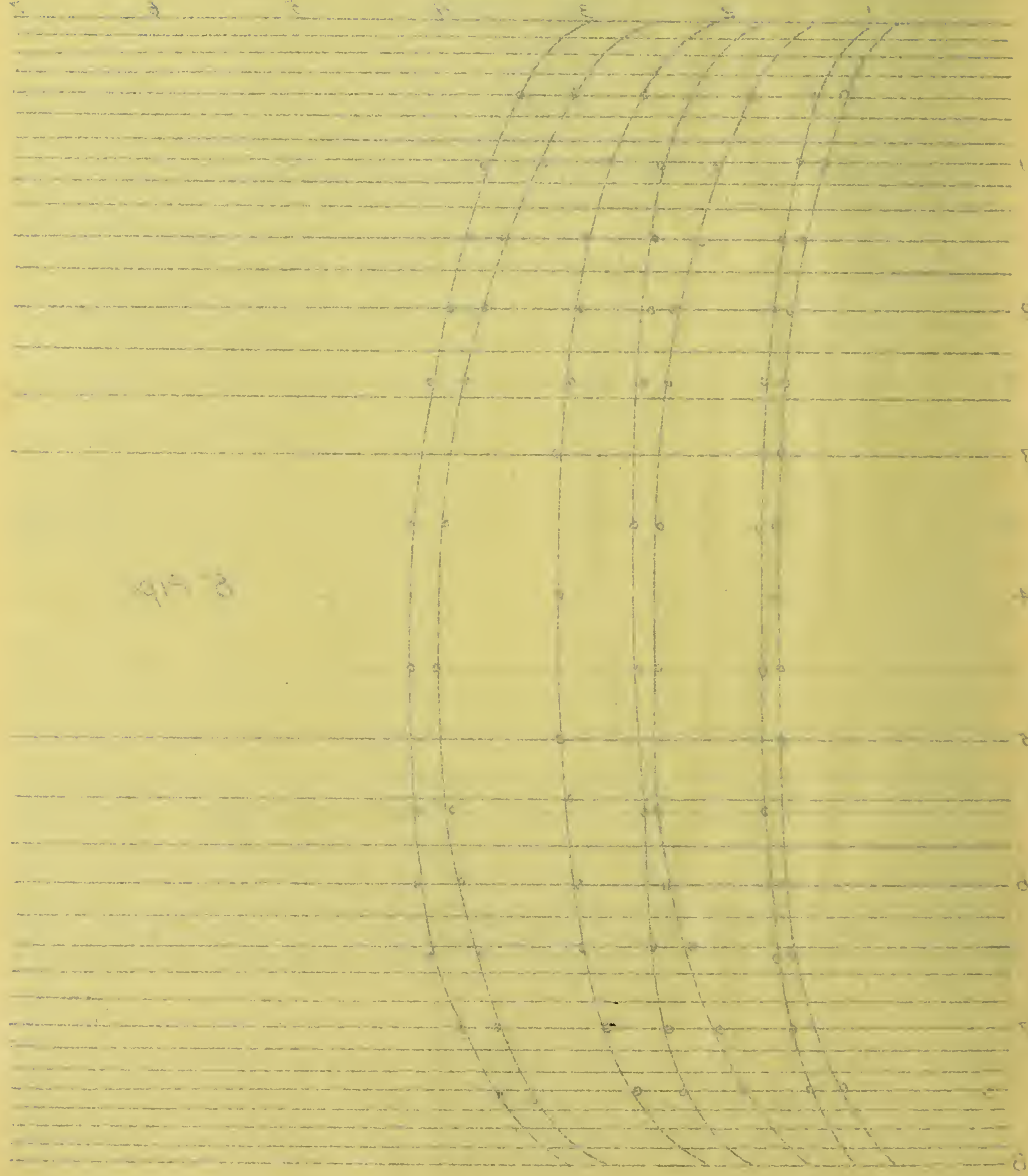


PLATE IV

Curves showing values of $\sqrt{h}$ using

Pitot Tube

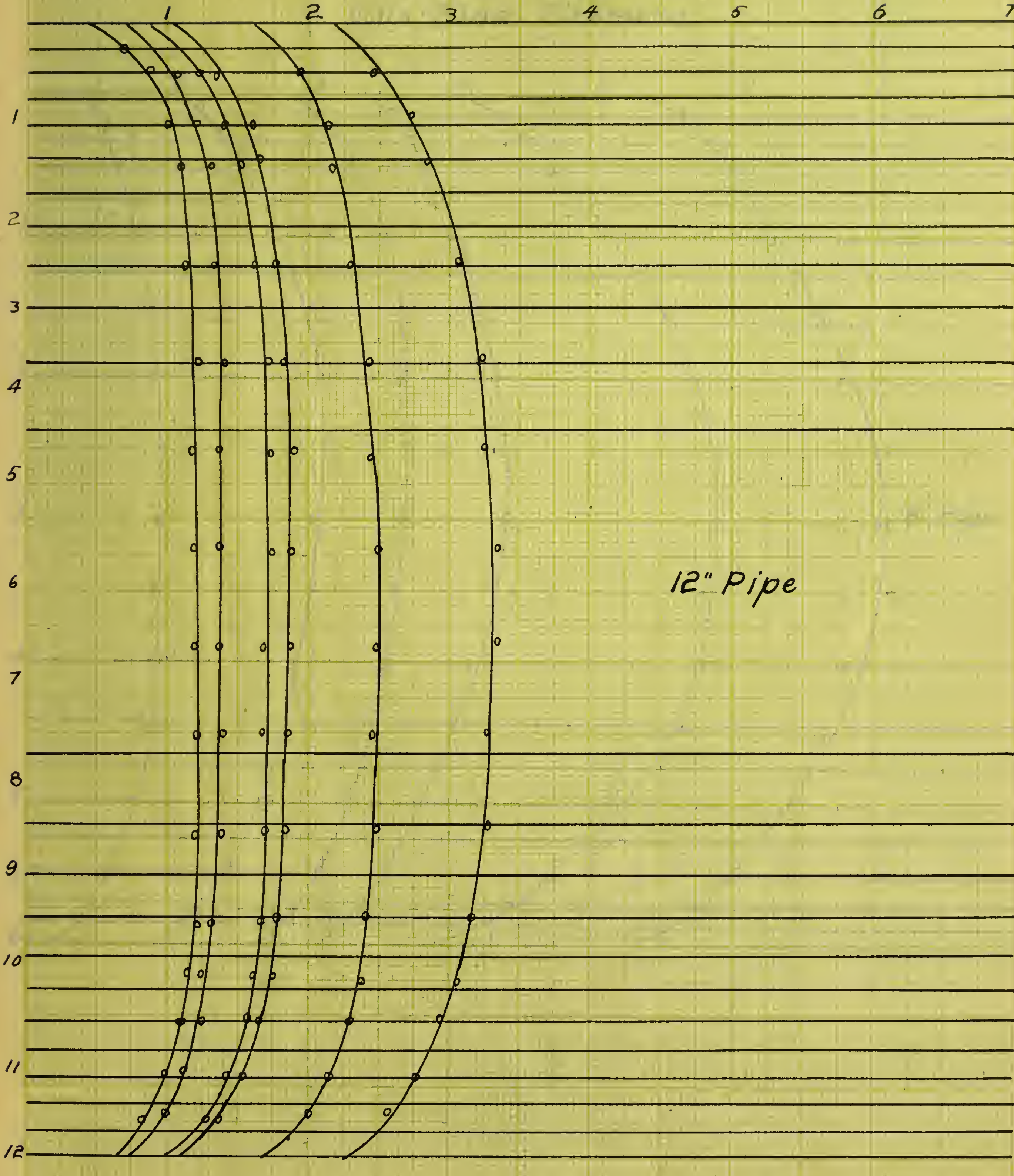


PLATE V

Curves showing values of $\sqrt{h}$ using

Cole-Flad Pitometer

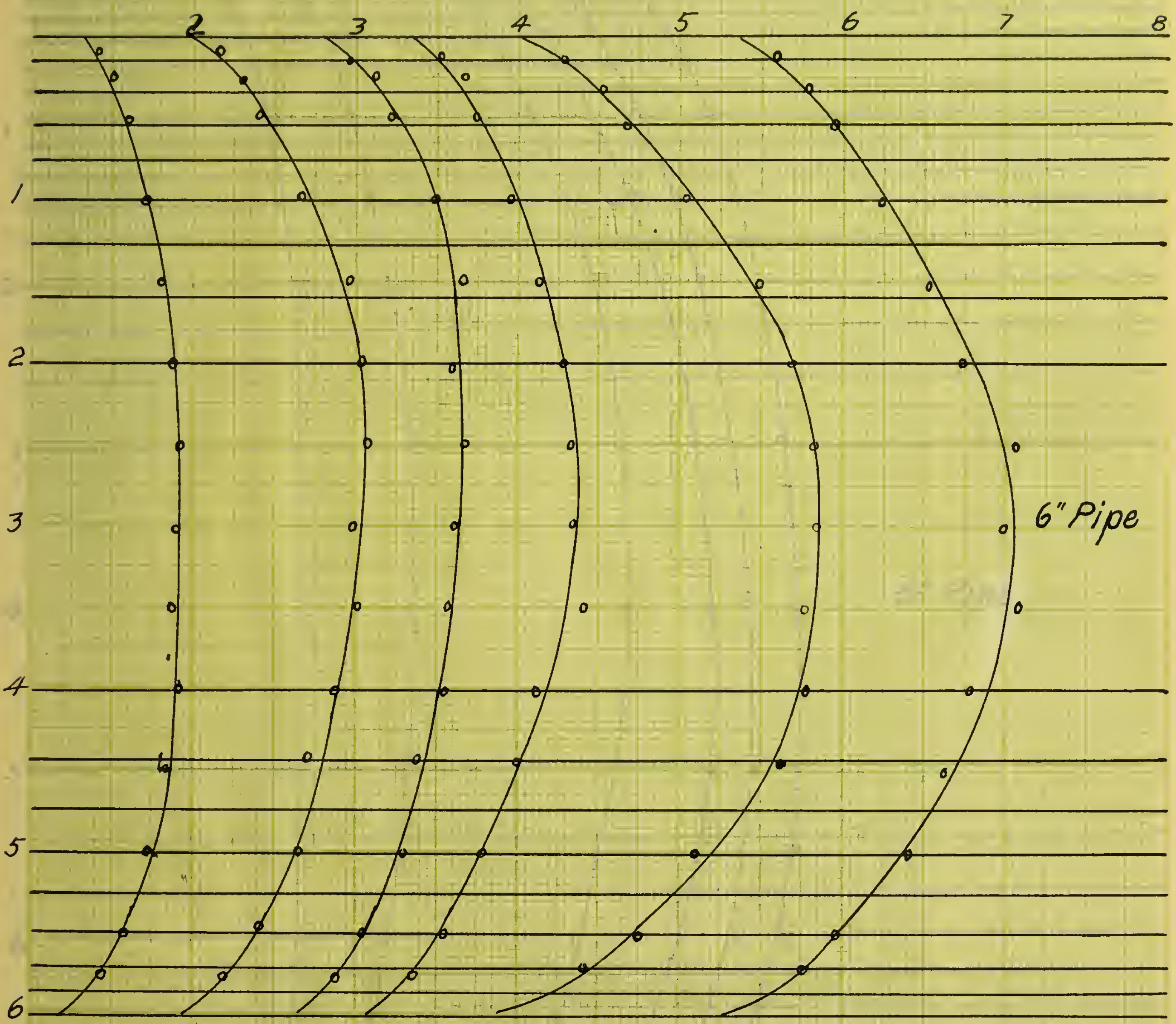


PLATE V

Curves showing values of $\sqrt{h}$ using

Cole-Pilot Pitometer

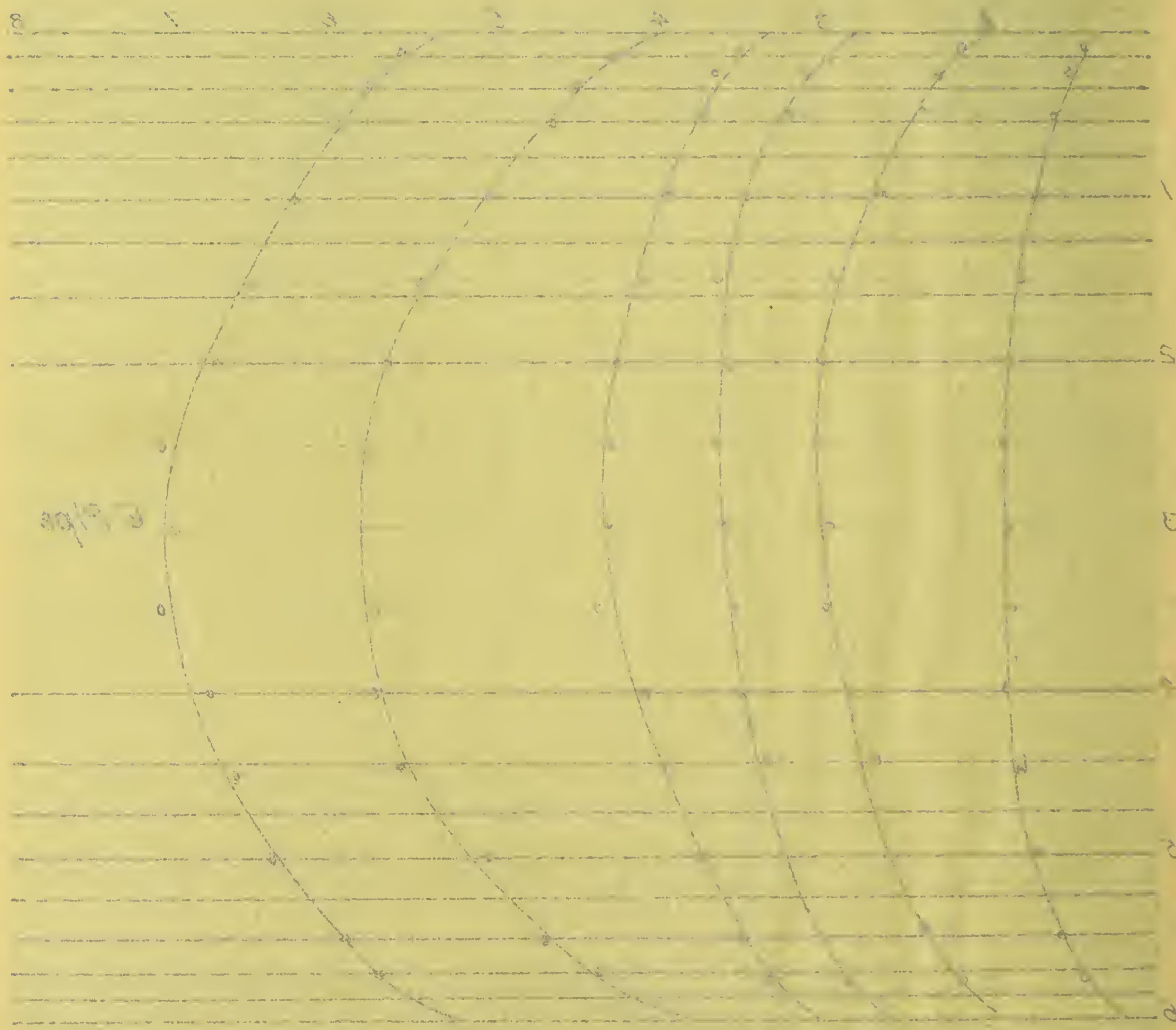


PLATE VI

Curves showing values of $\sqrt{h}$ using

Cole-Flad Pitometer

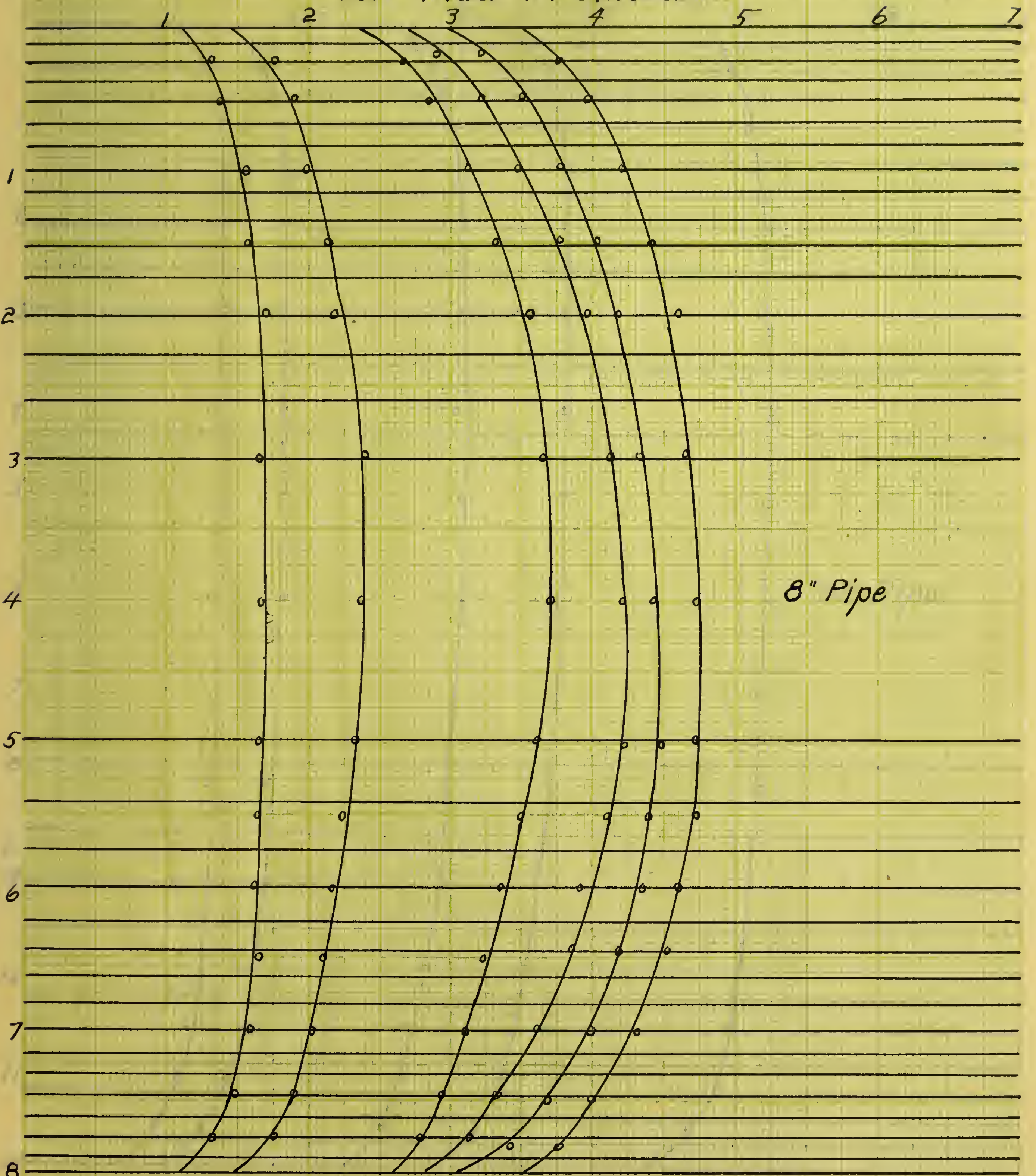
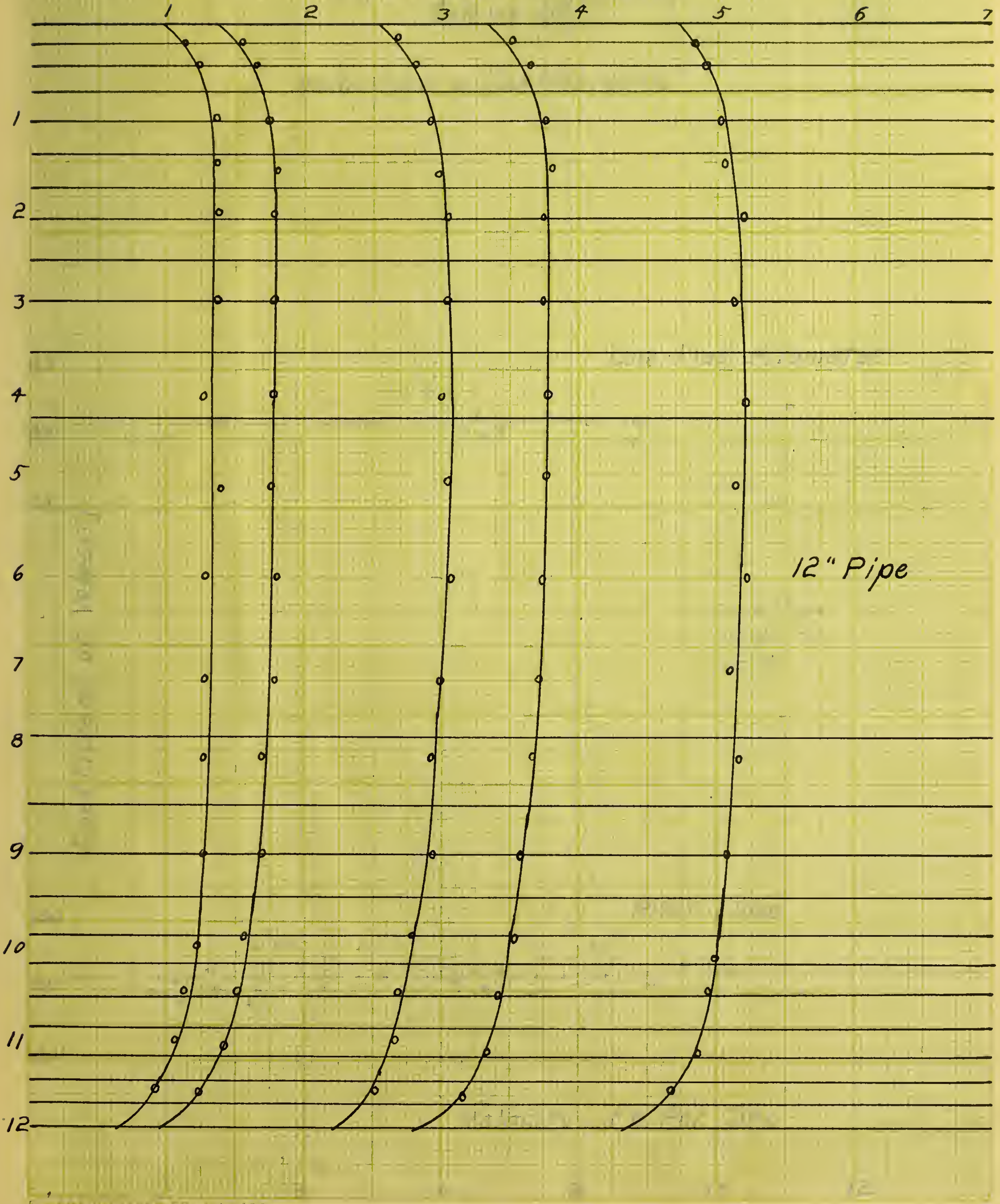
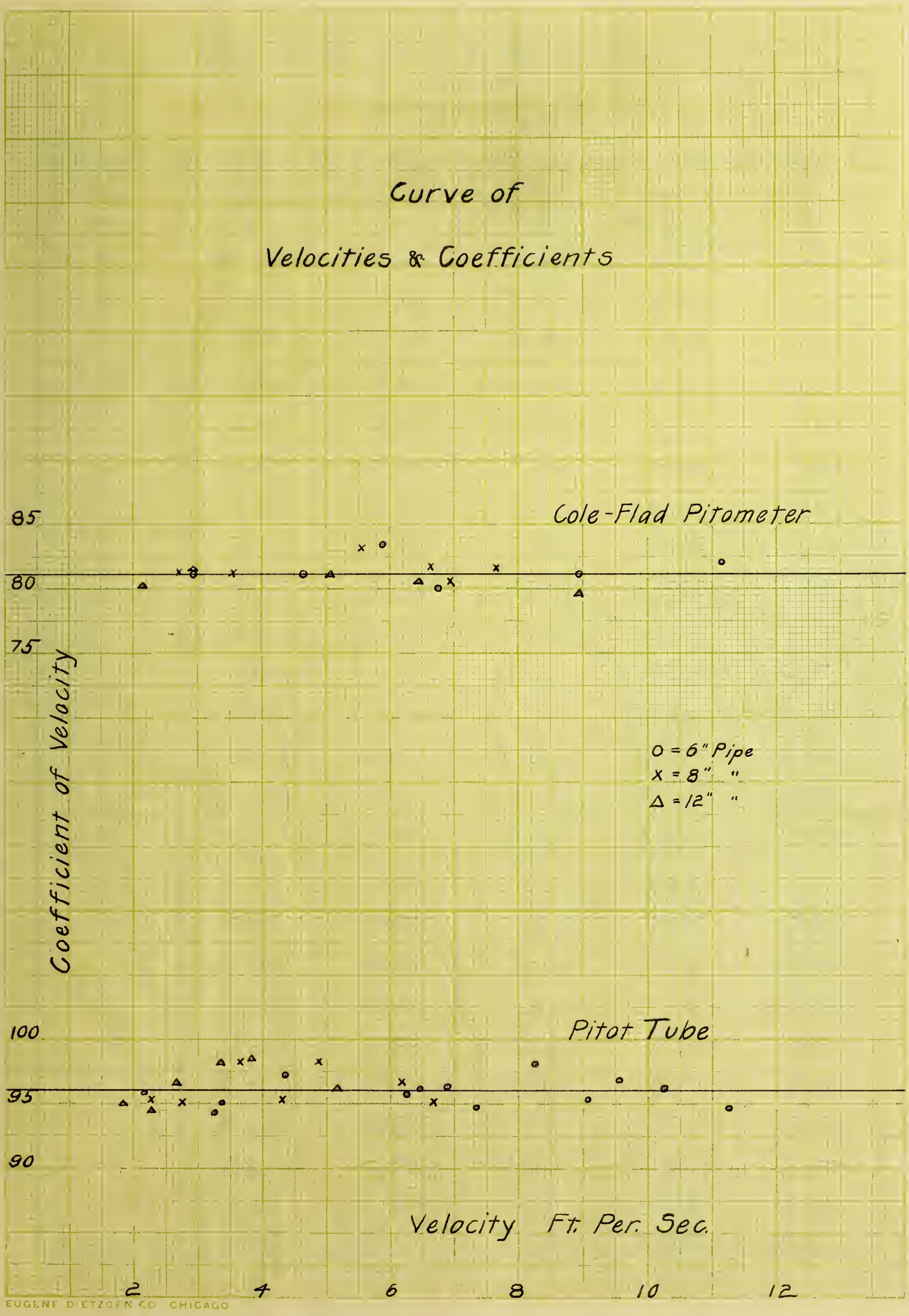


PLATE VII

Curves showing values of $\sqrt{h}$ using

Cole-Flad Pitometer





Curve of
Velocities & Coefficients
Cole-Flad Pitometer
85
80
75
Coefficient of Velocity
O = 6" Pipe
X = 8" "
Δ = 12" "
Pitot Tube
100
95
90
Velocity Ft. Per. Sec.
2
4
6
8
10
12
EUGENE DIETZGEN CO. CHICAGO

RESULTS OF EXPERIMENTS WITH PITOT TUBE

Size of Pipe in	Actual Velocity Ft. Per. Sec. V	Indicated Velocity Ft. Per. Sec. V'	Indicated Center Velocity Ft. Per. Sec. V_c	V/V' Coefficient C	V'/V_c
6	2.08	2.19	2.59	.958	.846
"	3.01	3.23	3.68	.941	.877
"	3.23	3.39	3.93	.950	.863
"	4.21	4.43	5.20	.971	.850
"	6.01	6.28	6.89	.957	.911
"	6.21	6.46	7.26	.962	.890
"	6.65	6.90	7.82	.964	.883
"	7.00	7.39	7.89	.948	.913
"	8.15	8.25	9.04	.981	.912
"	8.62	9.04	10.29	.953	.877
"	9.84	10.22	11.72	.962	.872
"	10.65	11.26	13.07	.946	.853
8	2.28	2.43	2.89	.951	.843
"	2.58	2.72	3.13	.950	.868
"	3.70	3.77	4.47	.983	.846
"	4.10	4.30	4.74	.953	.907
"	4.81	4.89	5.64	.985	.867
"	5.99	6.19	7.16	.968	.864
"	6.36	6.68	7.56	.950	.883
12	1.76	1.88	2.18	.930	.862
"	2.10	2.22	2.49	.945	.894
"	2.60	2.69	3.04	.968	.884
"	2.81	2.86	3.33	.983	.859
"	3.79	3.85	4.48	.985	.862
"	5.01	5.19	5.92	.963	.877

RESULTS OF EXPERIMENTS
WITH
COLE-FLAD PITOMETER

Size of Pipe in.	Actual Velocity Ft. Per Sec. V	Indicated Velocity Ft. Per. Sec. V'	Indicated Center Velocity Ft. Per. Sec. V_c	V/V' Coefficient C	V'/V_c
6	2.42	2.98	3.45	.812	.864
"	3.75	4.63	5.46	.812	.848
"	4.81	5.90	6.57	.835	.881
"	5.52	6.77	7.86	.800	.861
"	7.24	8.93	10.50	.811	.849
"	9.14	11.13	12.62	.821	.872
8	2.20	2.70	3.03	.814	.889
"	2.92	3.58	4.26	.811	.840
"	4.58	5.57	6.62	.832	.841
"	5.47	6.68	7.62	.818	.888
"	5.61	6.97	7.97	.805	.875
"	6.23	7.63	8.50	.816	.898
12	1.70	2.13	2.33	.801	.914
"	2.36	2.90	3.13	.812	.926
"	4.06	5.01	5.46	.811	.917
"	5.18	6.44	6.71	.805	.959
"	7.15	8.97	9.25	.796	.969